ISSN: 2278 – 1323
International Journal of Advanced Research in Computer Engineering & Technology (IJARCET)
Volume 2, Issue 7, July 2013

# Thermal nondestructive testing and spice simulation with approach of electro-thermal modelling

**Chinmayee Jena, Alok Kumar Singh**

*Abstract*— **Non-destructive testing (NDT) refers to all the test methods, which permit testing or inspection of object without impairing its future usefulness. The aim of NDT is the detection of damages or unwanted irregularities like flaws, inclusions, material loss/degradation and local imperfections in material properties. Active infrared thermography is a nondestructive evaluation technique in which material is thermally stimulated by heat source and an infrared camera is generally used to record the resulting thermal transient at the surface of material. As the heat diffuses inside the materials, it gets perturbed by the presence of sub-surface defects, causing a temperature contrast at the surface, which is used for finding sub-surface defect. It is relatively fast, safe and non-contact and easy to use technique for large area scans. This sector presents the comparison between the experimental and simulated results obtained from 3D electrical model of active thermography using SPICE (Simulation Program with Integrated Circuit Emphasis). In the present work, this approach has been exploited in the interest of some active infrared thermography problems.**

***Index Terms-Non-destructive testing(NDT),Active infrared thermography, sub-surface defects, SPICE (Simulation Program with Integrated Circuit Emphasis), 3D electrical model.***

## I. Introduction

NDT encompasses activities like real-time monitoring during manufacturing, inspection of assemblies for tolerances, alignment, and periodic in-service monitoring of flaw/damage growth in order to determine the maintenance requirements. The art of NDT is used in many fields without even being considered in the realm of NDT. Initially NDT was used primarily for process control and secondarily for quality control. Later, the use of NDT was recognized as a means of meeting consumer demands for better products, reduced cost and increased production.

In recent years industries are heavily dependent on the in-situ testing of the product inside the assembly line in order to ensure 100% reliability. A group of NDT scientists deals with defects inside material. There exist many well established techniques with which hidden defects inside the material can be found out, e.g. ultrasonic testing-ray imaging etc. The main problem with ultrasonic NDT is that it is a contact process and hence takes a lot of time to scan the surface point by point. On the other hand, X-ray imaging is a whole field technique but it is costly [1].TNDT stands for a new method in NDT which uses thermal wave for sub-surface defect detection. This is also a whole field technique. Here the sample under test produces unequal surface heating on external heat stimulus which in turn carries the signature of hidden defects inside the sample [2-3].

The discovery, by Sir William Herschel in 1800, of thermal radiation, outside the visible part of the light spectrum, marked the beginning of a new era in science and technology. By placing a thermometer beyond the red part of the spectrum produced by a prism, he proved the presence of an invisible radiation (christened infrared) that obeyed the same laws as visible radiation, but was characterized by its heating effect. Following Herschel, further milestones continued to be set [Maldague, 2001]. In 1829, a detector of infrared (IR) radiation was developed based on the thermocouple principle [4-5]. Herschel's son, Sir John, produced the first IR image using an evaporograph, in 1840. Max Planck's theory of radiation gave a theoretical foundation to Herschel's experiments in 1900. Subsequently, progress in IR technologies accelerated.

In this chapter, electrical equivalence of heat conduction is described by direct comparison of differential equations describing, voltage variation in a loss transmission line, with temperature variation in one-dimensional (1-D) heat conduction [5]. Using the correspondence between the fundamental laws of heat transfer and electricity, 1-D, 2-D and 3-D electro-thermal models have been given for finding direct solutions of active thermography problems.

These models can be simulated and solved by a wide variety of circuit simulators, without the need for dedicated thermography software. In the present work, electro-thermal models of samples have been generated by a computer program and the resulting networks are simulated by a commonly used circuit simulator PSpice: member of the well-known SPICE (Simulation Program with Integrated Circuit Emphasis) family of circuit simulators [6]. The simulation results give direct solutions of the active thermography problem. Further, as a specific application, the method has been used in estimating heat flux requirement for detection of a known sub-surface defect in a mild-steel material.

## II. Electro-thermal modeling for active thermography

### A. 1D Modeling

#### 1) Heat Conduction:

***Chinmayee Jena***, *Electronics and Communication Department, ABES Engineering College, Ghaziabad, India,*
***Alok Kumar Singh***, *Electronics and Communication Department, ABES Engineering College, Ghaziabad, India.*

The equivalence of heat conduction to a specific circuit model can be most easily visualized by directly comparing the differential equations describing voltage variation in a loss transmission line having negligible inductance and leakage, with that describing temperature variation in 1D heat conduction. Temporal (t) and spatial (x) temperature (T) variation resulting from 1D heat flow in materials, is described by [Carslaw & Jaeger, 1959]

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho\, c}{k}\frac{\partial T}{\partial t} \quad \text{.................................(2.1)}$$

Where ρ , c and k are the mass density, specific heat and thermal conductivity of the material respectively. Above equation can be expanded as:

$$\frac{\partial^2 T}{\partial x^2} = \frac{C'}{k\, A\, \Delta d}\frac{\partial T}{\partial t} \quad \text{.................................(2.2)}$$

Where C', A and Δd are the heat capacity, area of cross-section and small thickness element of material respectively. Similarly, the differential equation describing temporal and spatial voltage (V) variation (the 'telegraph equation'), in a lossy transmission line having negligible inductance and leakage, is given by [Kreyszig, 1999]

$$\frac{\partial^2 V}{\partial x^2} = R_l C_l \frac{\partial V}{\partial t} \quad \text{................................(2,3)}$$

Where Rl and Cl are the resistance per unit thickness and capacitance per unit thickness respectively. Above equation can also be expanded as:

$$\frac{\partial^2 V}{\partial x^2} = \frac{C}{\sigma\, A\, \Delta l}\frac{\partial V}{\partial t} \quad \text{.........................(2.4)}$$

Where C and σ are the electrical capacitance and electrical conductivity respectively. Comparing Eq. (2.2) and Eq. (2.4), the apparent physical correspondences are:

$T \leftrightarrow V, \quad k \leftrightarrow \sigma, \quad C' \leftrightarrow C,$ ..........................(2.5)

A material of thickness element Δd, cross section area A, thermal conductivity k, density ρ and specific heat c, can be electrically modeled by an equivalent resistance R and capacitance C, using above equivalence between thermal and electrical parameters [Cheng et al., 2000]

$R = \Delta d / kA$ .............................................(2.6)
$C = \rho\, A\, \Delta d\, c$ .............................................(2.7)

Correspondence between the fundamental laws of heat transfer and electricity permit conversion of heat transfer problem into an electrical problem for ease of understanding and solving [8]. These associations, which work in both one-dimensional and multi-dimensional permanent and transient regimes, are based on the following similarity [Maldague, 2001a]

q=ΔT/ Rth (Heat transfer side)↔ I = ΔV/R (Electrical side)...(2.8)

Where q, ΔT and Rth are the rate of heat transfer, temperature difference and thermal resistance (in thermodynamic units), and I, ΔV and R are the, current, voltage difference and electrical resistance (in electrical units). Above relation shows that the rate of heat transfer is analogous to electrical current[7-8]. This equivalence is used to model rate of incident heat energy as an equivalent value current source.

Based on the above electro-thermal analogy, a 1-D transient heat conduction problem can be modeled electrically by dividing the given length of sample material into smaller sections, with the corresponding R and C values for each section, as stated in Eqs.(2.6) and (2.7). Fig. 2.1 shows the equivalent electrical model of 1D transient heat conduction having a heat source at one end for transient thermography. The complete length has been divided and modeled in five equal stages or sections for illustration. The incident rate of heating at one end is modeled as a current source [9]. A high value of resistance or reverse biased diode can be connected at the other end to make the circuit complete simulation and analysis. It will prevent heat (current) flow from the material to the surrounding medium: a valid assumption in most of the cases of thermography, since air is a very good thermal insulator.

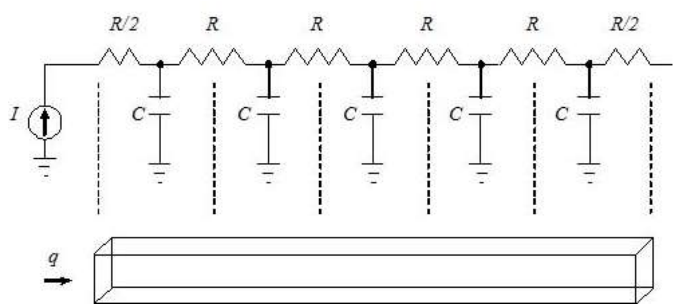


Fig. 2.1One-dimensional equivalent electrical model of heat conduction for active thermography.

For including the effect of other modes of heat transfer i.e. convection and radiation, an equivalent electrical resistance corresponding to the thermal resistance offered by the other modes of heat transfer [10-12]. It may be connected at nodes corresponding to all surface boundaries. These can be modeled as an equivalent resistance [Maldague, 2001a] if their respective heat transfer coefficients are known.

*2) Heat Convection:*

Heat transfer through convection can be modeled as an equivalent resistance Rconv of value:

$R_{conv} = 1/ h S$ ………………………………(2.9)

Where S is the surface area and h is convective coefficient, which depends on the temperature, physical dimensions and position of the surface and thermal proprieties of fluid. The value of h for free convection is given by the following relation [Todd & Ellis, 1982].

$h = C1 (k/L) (Gr . Pr^m$ …………………,,,.(2.10)

Here Gr and Pr Grashof number and Prandtl number and L is significant vertical length. The value of 'm' depends on the product of Grashof and Prandtl number, and value of C1 depends on the product of Grashof and Prandtl number as well as shape and position of the surface.

*3) Heat radiation*

Similarly, heat transfer due to radiation can also be modeled as an equivalent resistance Rrad of value [Maldague, 2001a]:

$R_{rad} = 1/ hr S$ …………………….(2.11)

Where, hr is given as

hr = σ FQ-P (TQ4 – TP4 / TQ – TP) ………...(2.12)

Here σ is Stefan-Boltzmann constant, FQ-P is thermal radiation shape factor specify the part of energy leaving from the surface Q and reaching to other surface P, and TQ and TP and the temperature of the surface Q and P, respectively.

Both h and hr depends on many parameters as well as temperature of the object. It is not possible to find out the fixed value of these coefficients in transient conditions. However in case of thermal NDT, conduction generally plays a dominant role (depending on the Biot number) as compared to other modes of heat transfer [11]. Therefore the exact values of these coefficients are not very crucial for estimation of temperature evolution. However in most of the cases convection and radiation losses are not very significant and can be ignored in transient thermal NDT [Maldague, 2001b].

*B. 2D Modeling*

The same approach of 1D modeling is extended for 2D model of active thermography. Fig. 2.2 shows the 2D electrical model of heat conduction for active thermography. The entire surface of the object is firstly divided into smaller elements, which are then electrically modeled with R and C values (from Eqs. (2.6) and (2.7) respectively), at representative nodes of defect as well as non-defect regions of the object. In 2D model, surface elements of the object in front of incident radiations are connected with current sources depending on the incident heat flux and its surface area.

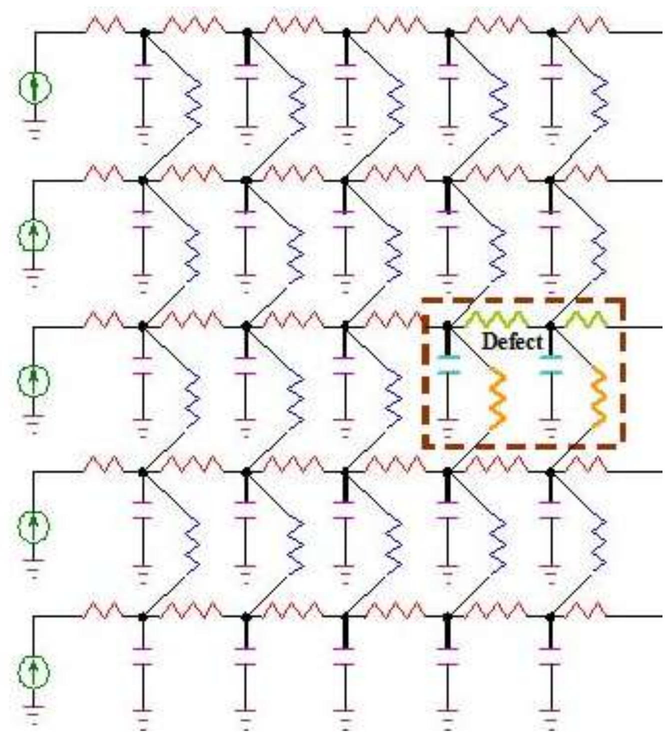


Fig. 2.2 Two-dimensional equivalent electrical model of heat conduction for active thermography. Different colors of resistances and capacitances represent different values, corresponding to different directions or materials (defects). The resistance and capacitance values in the defect region will be according to the local thermal properties.

*C. 3D Modeling*

Further, the same approach has been used for 3D electrical model of active thermography. Thermal conduction in the object was modeled by dividing it into cuboids as shown in Fig. 2.3. Electrically equivalent resistances and capacitances in different directions of the cuboids for the defective and non-defective regions of the object have been modeled using Eqs. (2.6) and (2.7). By appropriately connecting all cuboids, forms a 3D RC network of the object. Front side elements facing the incident radiation are connected with appropriate value of current sources.

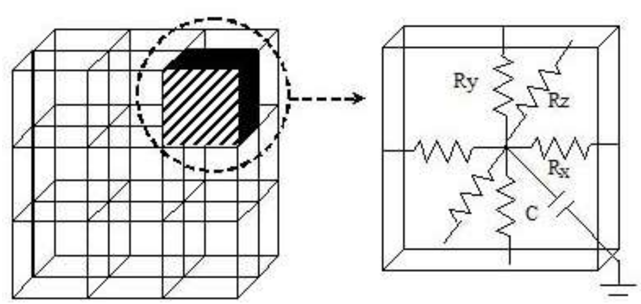


Fig. 2.3 Three-dimensional equivalent electrical model of heat conduction for active thermography.

## III. INSTRUMENTATION

### A. Basic Blocks of the Sysytem

Fig. 3.1 shows the basic blocks of the system. The computer controlled heat-sources heat the sample under test. The exact nature of the heating depends on the algorithm of defect detection [12]. The profile of the surface temperature of the sample is recorded using a thermal camera and is stored into a computer for offline analysis.

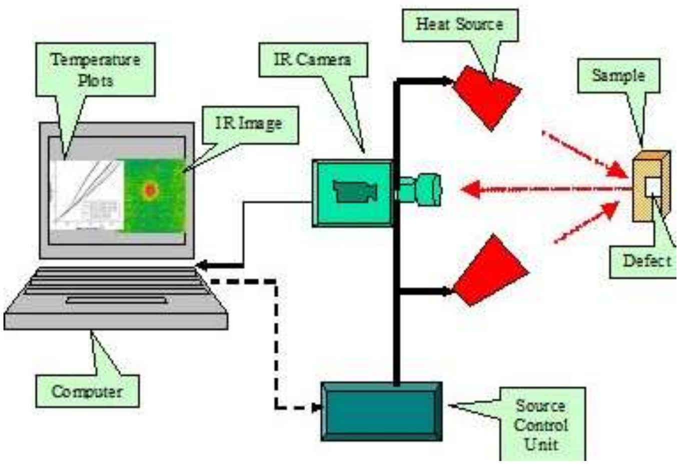


Fig.3.1 Schematic of typical active infrared thermography setup.

### B. Heating Control Unit

Heat sources play a major role in active thermography. In fact, all the techniques in active thermography are named after the kind of heating applied to the sample. From the user's point of view, it therefore becomes important to be able to choose the type of heating and consequently the corresponding processing algorithm for detection [11]. This enables any type of active thermography to be carried out using the same setup. The design and implementation of the heating control unit, its driver and the software inter-face is going to be the part of the system development.

### C. Image Capture Unit

To integrate all the blocks into one system, the dependency to the commercially available frame-grabber card has to be removed because of the some reasons like 10-12 bit frame-grabber card are not readily available, The frame-grabber cards does not come with APIs and Better understanding of computer architecture[2].

### D. Software

The system will have user-friendly software front-end with the following features like Simulation module which will act as an expert suggestion window, integrated control over excitation and frame-capture, different online analysis module for e.g. Pulse-phase, FMTWI etc [6].

## IV. IMPORTANT PARAMETERS CALCULATED FROM THERMOGRAM

### A. Thermal contrast

A thermogram (in fact any digitized image ) is nothing but collection of pixels. The intensity at each pixel represents the temperature of the corresponding region on the sample surface. In case of active thermography, generally a sequence of such thermal images (i.e. a movie) is taken and the time evolution of the surface temperature is studied. One of the parameter that could be extracted from the movie is known as the Thermal Contrast [1]. It is defined as follows:

$$C(t) = \frac{T_{def}(t) - T_{def}(0)}{T_S(t) - T_S(0)} \quad \text{……………..(3.1)}$$

Where $T_{def}$ (t) is the temperature over the defective region at time t while $T_S$(t) is that over a sound region. The subtraction from the initial frame makes the thermal contrast less sensitive to surface properties. The plot of thermal contrast vs. time over a defective region of the sample goes through a peak value at some time $t_{max}$ which is a characteristic of the defect depth.

### B. Phase and magnitude image

For active thermography the sample is given a stimulus. No matter what type of excitation is given to the sample, it can be broken down into its sin and cos component with the help of the Fourier Theorem. Thus a thermal movie can be treated as a super-position of multiple heating excitations having different frequencies. Being a diffusing media, different frequencies can penetrate into the material by different depths. If throughout the movie, the temperature of a single pixel on the thermogram is recorded, it gives rise to a time series. A Fourier analysis of this time series at a given frequency leads to two parameters i.e. magnitude and phase. The above operation can be repeated for each pixels of the thermogram generating the magnitudeand phase data for each pixel. A special plot of phase and magnitude data at a givenfrequency reveals the defects at some specific depth. Lower the frequency is chosen, deeper into the sample can be probed.

## V. EXPERIMENTAL AND SPICE SIMULATION RESULTS

This section presents the comparisons between the experimental and simulated results obtained from 3D electrical model of active thermography [4]. Direct solution obtained from 3D model has been used for prediction of absolute thermal contrast (temperature difference over the defect and non-defect region) and estimation of minimum heat flux requirement for the mild steel sample.

*A. Mild Steel Sample*

Active thermography experiments have been performed on a 13 mm thick, mild-steel sample, having a blind hole of 20 mm diameter at a depth of 2.25 mm from the front surface {sample size}. An infrared image of thermally irradiated sample is shown in Fig. 4.1 which the subsurface defect is clearly visible.

A heat source of 1500 W made up of 3 halogen tubes of 500 W each, having a mechanically operated shutter for switching on/off the emitted radiations has been used for heating the sample. In the experiment, the heat source was placed parallel to the sample for uniform heating as shown in the experimental setup (Fig. 3.1). Temperatures over the defect and non-defect region of the sample have been monitored and recorded by a computer interfaced close focused IR thermometer (Raytek MX4) and a camera (NEC TH 5104).

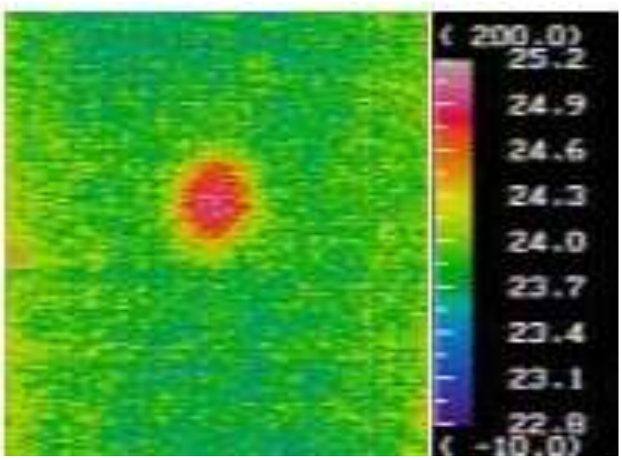


Fig.4.1 Infrared image of the mild-steel sample showing sub-surface defect.

To obtain the experimental data for validation of electrical modeling and to demonstrate its application for prediction of thermal contrast and estimation of minimum heat flux requirement for a given sample, three sets of experiments have been performed. In the experiments, sample was heated for the duration of 6 s with the radiative heat flux of 5.60, 2.40 and 0.46 kW/m2 by keeping the heat source at increasing distances of 25, 35 and 75 cm, respectively, from the sample. In the present study, emphasis is only on the effect of amplitude of heating, instead of time duration of heating. Therefore, all experiments have been performed for the same value of heat pulse duration (6 s). The front surface of the sample was coated with a thin layer of carbon to achieve uniform and high emissivity and absortivity values.

Fig. 4.2 shows the plot of absolute thermal contrast as a function of time for a heat flux of 5.6 and 2.4 kW/m2. Absolute thermal contrast corresponding to the heat flux of 0.46 kW/m2 could not be obtained because of the limited resolution (0.1oC) of the IR thermometer and camera.

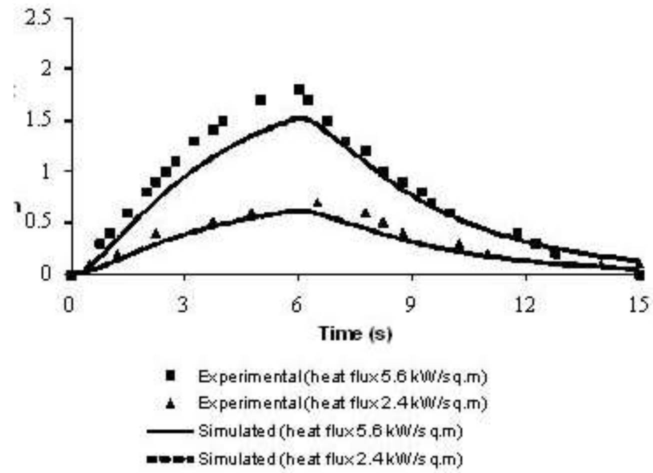


Fig. 4.2 Experimental and PSpice simulated absolute thermal contrast plots of the mild-steel sample, for heat flux values of 5.6 and 2.4 kW/m$^2$

A 3D RC network model of transient heat conduction has been used for the simulations of the above-mentioned experiments on mild-steel sample. The resulting model has been simulated by a very well known and commonly used electrical circuit simulator software Pspice; member of the well-known SPICE (Simulation Program with Integrated Circuit Emphasis) family of circuit simulators. A similar approach, for other physical phenomena, whose electrical equivalent circuits are realizable, has been reported earlier. Simulation was performed by dividing the sample into 9 planes of (9 X 9) sections, each of size 6.66 mm X 6.66 mm X 1.5 mm. Resistance and capacitance values of sample sections were calculated using Eqs (2.6) and (2.7). Values for the defect region (blind hole) took into account the thermal properties of air. Diodes are used at the boundaries of the RC network to make the circuit complete for simulation and to prevent heat flow from material to surroundings. In the simulation, heat transfer through convection and radiation has been modeled and considered negligible. Incident heating on the sample has been modeled as a current pulse (explained in the section of modeling), of similar duration (6 s) as in the experiment, and amplitude equal to the rate incident energy falls on the front surface elements of the sample. In the electro-thermal model based SPICE simulation technique for predicting thermal response of the samples has been presented. In this section, the use of the same technique is extended for optimizing the time duration of heat source for mild steel structure.

Three sets of simulation have been performed with different values of current corresponding to the three experiments with different values of heat flux. The value of current was calculated by multiply the area of the surface element (6.66 X 6.66 mm2) with the corresponding heat flux falling on the element. These current sources have been connected at the surface elements of the sample facing the heat radiation in simulation.

Computer program has been made for generating the codes of equivalent electrical network of the sample with given amount of heat flux for performing PSpice simulation.. Fig. 4.2 shows the PSpice simulated absolute thermal contrast of the surface as a function of time for heat flux of 5.60 and 2.40 kW/m2. The resulting plots matches well with the experimentally obtained points. It validates electrical modeling and SPICE simulation for active thermography.

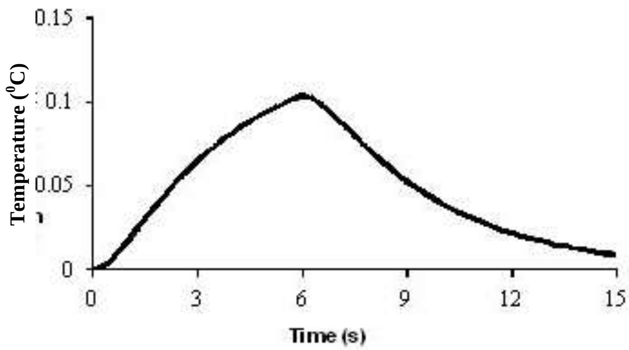


Fig. 4.3 PSpice simulated absolute thermal contrast plot of the mild-steel sample for heat flux value of 0.4 $kW/m^2$.

The Fig.4.3 shows the simulated absolute thermal contrast for heat flux of 0.46 kW/m2. The maximum absolute thermal contrast in this case was of the order of the resolution of thermal detectors therefore sub-surface defect could not be detected in corresponding experiment. This shows the lower limit of heat flux necessary to view defect in a given sample for a given heating time from the thermal detector of 0.1oC resolution.

## VI. CONCLUSION

We made a simplified electrical approach to transient heat conduction has been adopted for arriving at a novel one-dimensional electrical analysis. This method is quite insensitive to non-uniform heating. This type of modeling and simulation can be used for predication of surface temperature evolution, thermal contrast and estimation of heat flux requirement. This paper presents the comparison between the experimental and simulated results obtained from 3D electrical model

The resulting plots matches well with the experimentally obtained points. It validates electrical modeling and SPICE simulation for active thermography. This paper also reflects some world trends in the TNDT theory. In some cases, results are equivalent from the qualitative point of view. However, some techniques are best suited than others in quantification stages.

## ACKNOWLEDGEMENTS

The authors thank to NDT Lab (IIT Delhi) for research support.

## REFERENCES

[1] A. Levy, A. Dayan, M. Ben-David, and I. Gannot, 'A new thermography based early detection of cancer approach based on magnetic nanoparticles Theory simulation and in vitro validation (in press)', Nanomedicine: Nanotechnology, Biology and Medicine, doi:10.1016/j.nano.2010.06.007, 2010.

[2] F. Amon and C. Pearson, 'Thermal imaging in firefighting and thermography applications', Experimental Methods in the Physical Sciences, 43, pp 279-331,2010.

[3] Louaayou, N. Naït-Saïd, and F.Z. Louai, '2D finite element method study of the stimulation induction heating in synchronic thermography NDT', NDT&E International, 41(8), pp 577-581, 2008.

[4] P. Chaudhuri, P. Santra, S. Yoele, A. Prakash, D.C. Reddy, L.T. Lachhvani, J.Govindarajan, and Y.C. Saxena. 'Non-destructive evaluation of brazed joints between cooling tube and heat sink by IR thermography and its verification using FE analysis', NDT&E International, 39(2), pp 88-95, 2006.

[5] C. Ibarra-Castanedo and X. Maldague. "Pulsed Phase Thermography Reviewed,"QIRT J., 1(1):47-70, 2004.

[6] C. Ibarra-Castanedo, N. P. Avdelidis and X. Maldague. "Quantitative assessment of steel plates using pulsed phase thermography," Materials Evaluation, 63(11): 1128-1133, November 2005.

[7] C. Ibarra-Castanedo and X. Maldague. "Interactive methodology for optimized defect characterization by quantitative pulsed phase thermography," Research in Nondestructive Evaluation, 16(4):1-19, 2005.

[8] Maldague X P V: Theory and Practice of Infrared Thermography for Non- destructive Testing, John Wiley & Sons Inc., 2001.

[9] Zweschper Th, Dillenz A, Riegert G, Scherling D and Busse G: Ultrasoundexcited thermography using frequency modulated elastic waves. Insight, Vol 45 No 3, March 2003, pp 1-5.

[10] Tuli S, Mulaveesala R: Frequency-Modulated wave Thermography for Non- Destructive Testing. Proceedings QIRT 2004, 2004, pp H.6.1-6.6.

[11] Tuli S, Mulaveesala R: Defect detection by pulse compression in frequency modulated thermal wave imaging. QIRT Journal.(communicated). Oct. 2004.

[12] Rakotoniaina J P, Breitenstein O, Langenkamp M: Localization of weak heat sources in electronic devices using highly sensitive Lock-in thermography, Material science and engineering,B91-92, 2002. pp 481-485.

**Chinmayee Jena** has taken birth in Orissa on June 26, 1981. She has received B.Tech (Hons.) in Electronics and Instrumentation from **Biju Patnaik University of Technology**, Orissa (2003).After that she has occupied with various organization including IIT, Delhi (3 year) upto 2011. She is currently pursuing her M.Tech (last semester), in ABES Engineering College, Ghaziabad, India. She is involved in non-destructive characterization of materials, and thermal wave imaging. She is having a membership of Indian Society for Technical Education.

**Alok Kumar Sin**gh has taken birth in Utter Pradesh on Sept 1, 1976. He received his B.Tech and M.Tech in Electronic Engineering from University of Allahabad, U.P (2000 and 2006) respectively. He is currently pursuing his PhD from the Shri. Jagdishprasad Tibrewala University (JJTU), Rajasthan. He Worked with CEDIT ALLAHABAD as an Assistant Professor in Electronics & Communication Department from 1st July 2000 to 30th June 2004. He is working with A.B.E.S. Engineering College Ghaziabad as an Associate Professor in Electronics & Communication Department from 1Aug 2006 to till date.